

A review of wildland fire spread modelling, 1990-present

1: Physical and quasi-physical models

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Abstract

In recent years, advances in computational power and spatial data analysis (GIS, remote sensing, etc) have led to an increase in attempts to model the spread and behaviour of wildland fires across the landscape. This series of review papers endeavours to critically and comprehensively review all types of surface fire spread models developed since 1990. This paper reviews models of a physical or quasi-physical nature. These models are based on the fundamental chemistry and/or physics of combustion and fire spread. Other papers in the series review models of an empirical or quasi-empirical nature, and mathematical analogues and simulation models. Many models are extensions or refinements of models developed before 1990. Where this is the case, these models are also discussed but much less comprehensively.

Introduction

History

The field of wildland fire behaviour modelling has been active since the 1920s. The work of Hawley (1926) and Gisborne (1927, 1929) pioneered the notion that understanding of the phenomenon of wildland fire and the prediction of the danger posed by a fire could be gained through measurement and observation and theoretical considerations of the factors that might influence such fires. Despite the fact that the field has suffered from a lack of

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readily achievable goals and consistent funding (Williams, 1982), the pioneering work by those most closely affected by wildland fire—the foresters and other land managers—has led to a broad framework of understanding of wildland fire behaviour that has enabled the construction of operational models of fire behaviour and spread that, while not perfect for every situation, at least get the job done.

In the late 1930s and early 1940s, Curry and Fons (1938, 1940), and Fons (1946) brought a rigorous physical approach to the measurement and modelling of the behaviour of wildland fires. In the early 1950s, formal research initiatives by Federal and State Government forestry agencies commenced concerted efforts to build fire danger rating systems that embodied a fire behaviour prediction component in order to better prepare for fire events. In the US this was through the Federal US Forest Service and through State agencies; in Canada this was the Canadian Forest Service; in Australia this was through the Commonwealth Forestry and Timber Bureau in conjunction with various state authorities.

In the 1950s and 60s, spurred on by incentives from defense budgets, considerable effort was expended exploring the effects of mass bombing (such as occurred in Dresden or Hamburg, Germany, during World War Two) and the collateral incendiary effects of nuclear weapons (Lawson, 1954; Rogers and Miller, 1963). This research effort was closely related to large forest or conflagration fires and had the spin-off of bringing additional research capacity into the field (Chandler et al., 1963). This resulted in an unprecedented boom in the research of wildland fires. The late 1960s saw a veritable explosion of research publications connected to wildland fire that dominated the fields of combustion and flame research for some years.

The 1970s saw a dwindling of research interest from defense organisations and by the 1980s, research into the behaviour of wildland fires returned to those that had direct interest in the understanding and control of such phenomena. By the 1980s, it was of occasional interest to journeyman mathematicians and physicists on their way to bigger, and more achievable, goals.

An increase in the capabilities of remote sensing, geographical information systems and computing power during the 1990s resulted in a revival in the interest of fire behaviour modelling, this time applied to the prediction of fire spread across the landscape.

Background

This series of review papers endeavours to comprehensively and critically review the extensive range of modelling work that has been conducted in recent years. The range of methods that have been undertaken over the years represents a continuous spectrum of possible modelling (Karplus, 1977), ranging from the purely physical (those that are based on fundamental understanding of the physics and chemistry involved in the combustion of biomass fuel and behaviour of a wildland fire) through to the purely empirical (those that have been based on phenomenological description or statistical regression of observed fire behaviour). In between is a continuous meld of approaches from one end of the spectrum or the other. Weber (1991a) in his comprehensive review of physical wildland fire modelling proposed a system by which models were described as physical, empirical or statistical, depending on whether they account for different modes of heat transfer, make no distinction between different heat transfer modes, or involve no physics at all. Pastor et al.

(2003) proposed descriptions of theoretical, empirical and semi-empirical, again depending on whether the model was based on purely physical understanding, of a statistical nature with no physical understanding, or a combination of both. Grishin (1997) divided models into two classes, deterministic or stochastic-statistical. However, these schemes are rather limited given the combination of possible approaches and, given that describing a model as semi-empirical or semi-physical is a ‘glass half-full or half-empty’ subjective issue, a more comprehensive and complete convention was required.

Thus, this review series is divided into three broad categories: physical and quasi-physical models; empirical and quasi-empirical models; and simulation and mathematical analogue models. In this context, a physical model is one that attempts to represent both the physics and chemistry of fire spread; a quasi-physical model attempts to represent only the physics. An empirical model is one that contains no physical basis at all (generally only statistical in nature), a quasi-empirical model is one that uses some form of physical framework upon which to base the statistical modelling chosen. Empirical and quasi-empirical models are further subdivided into field-based and laboratory-based. Simulation models are those that implement the preceding types of models in a simulation rather than modelling context. Mathematical analogue models are those that utilise a mathematical precept rather than a physical one for the modelling of the spread of wildland fire.

Since 1990, there has been rapid development in the field of spatial data analysis, e.g. geographic information systems and remote sensing. Following this, and the fact that there has not been a comprehensive critical review of fire behaviour modelling since Weber (1991a), I have limited this review to works published since 1990. However, as much of the work that will be discussed derives or continues from work carried out prior to 1990, such work will be included much less comprehensively in order to provide context.

Previous reviews

Many of the reviews that have been published in recent years have been for audiences other than wildland fire researchers and conducted by people without an established background in the field. Indeed, many of the reviews read like purchase notes by people shopping around for the best fire spread model to implement in their part of the world for their particular purpose. Recent reviews (e.g. Perry (1998); Pastor et al. (2003); etc), while endeavouring to be comprehensive, have offered only superficial and cursory inspections of the models presented. Morvan et al. (2004) takes a different line by analysing a much broader spectrum of models in some detail and concludes that no single approach is going to be suitable for all uses.

While the recent reviews provide an overview of the models and approaches that have been undertaken around the world, mention must be made of significant reviews published much earlier that discussed the processes in wildland fire propagation themselves. Foremost is the work of Williams (1982), which comprehensively covers the phenomenology of both wildland and urban fire, the physics and chemistry of combustion, and is recommended reading for the beginner. The earlier work of Emmons (1963, 1966) and Lee (1972) provides a sound background on the advances made during the post-war boom era. Grishin (1997) provides an extensive review of the work conducted in Russia in the 1970s, 80s and 90s.

This particular paper will discuss those models based upon the fundamental principles of the physics and chemistry of wildland fire behaviour. Later papers in the series will discuss those models based upon observation of fire behaviour and upon mathematical analogies to fire spread. As the laws of physics are the same no matter the origin of the modeller, or the location of the model, physical models are essentially based on the same rules and it is only the implementation of those rules that differs in each model. A brief discussion of the fundamentals of wildland fire behaviour covering the chemistry and physics is given, followed by discussions of how these are applied in physical models themselves. This is then followed by a discussion of the quasi-physical models.

Fundamentals of fire and combustion

Wildland fire is the complicated combination of energy released (in the form of heat) due to chemical reactions (broadly categorised as an oxidation reaction) in the process of combustion and the transport of that energy to surrounding unburnt fuel and the subsequent ignition of said fuel. The former is the domain of chemistry (more specifically, *chemical kinetics*) and occurs on the scale of molecules, and the latter is the domain of physics (more specifically, *heat transfer* and *fluid mechanics*) and occurs on scales ranging from millimetres up to kilometres (Table 1). It is the interaction of these processes over the wide range of temporal and spatial scales that makes the modelling of wildland fire behaviour a not inconsiderable problem.

Grishin (1997, pg. 81) proposed five relative independent stages in the development of a deterministic physical model of wildland fire behaviour:

1. Physical analysis of the phenomenon of wildland fire spread; isolation of the mechanism governing the transfer of energy from the fire front into the environment; definition of the medium type, and creation of a physical model of the phenomenon.
2. Determination of the reaction and thermophysical properties of the medium, the transfer coefficients and structural parameters of the medium, and deduction of the basic system of equations with corresponding additional (boundary and initial) conditions.
3. Selection of a method of numerical solution of the problem, and derivation of differential equations approximating the basic system of equations.
4. Programming; test check of the program; evaluation of the accuracy of the difference scheme; numerical solution of the system of equations.
5. Testing to see how well the derived results comply with the real system; their physical interpretation; development of new technical suggestions for ways of fighting wildland fire.

Clearly, stages one and two represent considerable hurdles and sources of contention for the best method in which to represent the phenomenon of wildland fire. This section aims to provide a background understanding of the chemistry and physics involved in wildland fire. However, it must be noted that even though these fields have made great advances in the understanding of what is going on in these processes, research is still very active and sometimes cause for contention (di Blasi, 1998).

Chemistry of combustion

The chemistry of combustion involved in wildland fire is necessarily a complex and complicated matter. This is in part due to the complicated nature of the fuel itself but also in the range of conditions over which combustion can occur which dictates the evolution of the combustion process.

Fuel chemistry

Wildland fuel is composed of live and dead plant material consisting primarily of leaf litter, twigs, bark, wood, grasses, and shrubs. (Beall and Eickner, 1970), with a considerable range of physical structures, chemical components, age and level of biological decomposition. The primary chemical constituent of biomass fuel is cellulose (of chemical form $(C_6O_5H_{10})_n$), which is a polymer of a glucosan (variant of glucose) monomer, $C_6O_6H_{12}$ (Shafizadeh, 1982; Williams, 1982). Cellulose is a linear, unbranched polysaccharide of $\simeq 10,000$ D-glucose units in $\beta(1,4)$ linkage³. The parallel chains are held together by hydrogen bonds, a non-covalent linkage in which surplus electron density on hydroxyl group oxygens is distributed to hydrogens with partial positive charge on hydroxyl groups of adjacent residues (Ball et al., 1999).

Other major chemical components of wildland fuel include hemicelluloses (copolymers of glucosan and a variety of other possibly monomers) and lignin (a phenolic compound) in varying amounts, depending upon the species, cell type and plant part (See Table 2). Minerals, water, salts and other extractives and inorganics also exist in these fuels. The cellulose is the same in all types of biomass, except for the degree of polymerisation (i.e. the number of monomer units per polymer). Solid fuel is often referred to as a *condensed phase* fuel in the combustion literature.

Cellulose is an extraordinarily stable polysaccharide due to its structure: insoluble, relatively resistant to acid and base hydrolysis, and inaccessible to all hydrolytic enzymes except those from a few biological sources. Cellulose is the most widely studied substance in the field of wood and biomass combustion; by comparison, few studies have been carried out on the combustion of hemicelluloses or lignin (di Blasi, 1998), due perhaps to the relative thermal instability of these compounds. The degradation of biomass is generally considered as the sum of the contribution of its main components (cellulose, hemicelluloses and lignin) but the extrapolation of the thermal behaviour of the main biomass components to describe the kinetics of complex fuels is only a rough approximation (di Blasi, 1998). The presence of inorganic matter in the biomass structure can act as a catalyst or an inhibitor for the degradation of cellulose; differences in the purity and physical properties of cellulose and hemicelluloses and lignin also play an important role in the degradation process (di Blasi, 1998).

³The D- prefix refers to one of two configurations around the chiral centre of carbon-5. The $\beta(1,4)$ refers to the configuration of the covalent link between adjacent glucose units, often called a glycosidic bond. There are two possible geometries around C-1 of the pyranose (or 5-membered) ring: in the β anomer the hydrogen on C-1 sits on the opposite side of the ring to that on C-2; in the α anomer it is on the same side. The glycosidic bond in cellulose is between C-1 of one β D-glucose residue and the hydroxyl group on C-4 of the next unit (see Figure 1).

Combustion reactions

Chemical reactions can be characterised by the amount of energy required to initiate a reaction, called the activation energy, E_a . This energy controls the rate of reaction through an exponential relation, which can be derived from first principles, known as the Arrhenius law:

$$k = A^{(-\frac{E_a}{RT})} \quad (1)$$

where k is the reaction rate constant, A is a pre-exponential factor related to collision rate in Eyring theory, R is the gas constant and T is the absolute temperature of the reactants. Thus, the rate constant, k , is a function of the temperature of the reactants; generally the higher the temperature, the faster the reaction will occur.

Solid phase reactions—competing processes

When heat is applied to cellulose, the cellulose undergoes a reaction called thermal degradation. In the absence of oxygen, this degradation is called *pyrolysis*, even though in the literature the term pyrolysis is often used incorrectly to describe any form of thermal degradation (Babrauskas, 2003). Cellulose can undergo two forms of competing degradation reaction: volatilisation and char formation (Figure 2). While each of these reactions involves the depolymerisation of the cellulose (described as the ‘unzipping’ of the polymer into shorter strands (Williams, 1982, 1985)), each has a different activation energy and promoting conditions, and result in different products and heat release.

Volatilisation generally occurs in conditions of low or nil moisture and involves thermolysis of glycosidic linkages, cyclisation and the release of free levoglucosan via thermolysis at the next linkage in the chain (Ball et al., 2004). This reaction is endothermic (requiring about 300 J g^{-1} (Ball et al., 1999)) and has a relatively high activation energy (about 240 kJ mol^{-1} (di Blasi, 1998)). The product, levoglucosan (sometimes described as ‘tar’ (Williams, 1982)), is highly unstable and forms the basis of a wide range of subsequent species following further thermal degradation that readily oxidise in the process of combustion, resulting in a multitude of intermediate and final, gas and solid phase, products and heat.

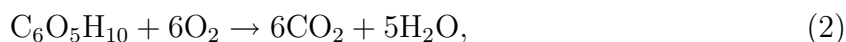
Char formation, on the other hand, occurs when thermal degradation happens in the presence of moisture or low rates of heating. In this competing reaction pathway, the nucleophile that bonds to the thermolysed carbo-cation at C-1 is a water molecule. The initial product is a reducing end which has ‘lost the opportunity’ to volatilise. Instead, further heating of such fragments dehydrates, polyunsaturates, decarboxylates, and cross-links the carbon skeleton of the structure, ultimately producing char. This reaction has a relatively low activation energy (about 150 kJ mol^{-1} (di Blasi, 1998)) and is exothermic (releasing about 1 kJ g^{-1}).

Thus, the thermal degradation of cellulose results in two competing pathways controlled by thermal and chemical feedbacks such that if heating rates are low and/or moisture is present, the charring pathway is promoted. If sufficient energy is released in this

process (or additional heat is added) or moisture evaporated, then cyclisation and the release of free levoglucosan from thermolysed, positively charged chain fragments, becomes statistically favoured over nucleophilic addition of water and char production. If the subsequent combustion of the levoglucosan and products releases enough energy then this process becomes self-supporting. However, if the heat released is convected away from the reactants or moisture is trapped, then the char-formation path becomes statistically favoured. These two competing pathways will oscillate until conditions become totally self-supporting or thermal degradation stops.

Gas phase reactions

Gas phase combustion of levoglucosan and its derivative products is highly complex and chaotic. The basic chemical reaction is assumed to be:



however, this assumes that all intermediate reactions, consisting of oxidation reactions of derivative products mostly, are complete. But the number of pathways that such reactions can take is quite large, and not all paths will result in completion to water and carbon dioxide.

As an example of a gas-phase hydrocarbon reaction, Williams (1982) gives a non-exhaustive list of 14 possible pathways for the combustion of CH_4 , one of the possible intermediates of the thermal degradation of levoglucosan, to H_2O and CO_2 . Intermediate species include CH_3 , H_2CO , HCO , CO , OH and H_2 .

At any stage in the reaction process, any pathway may stop (through loss of energy or reactants) and its products be advected away to take no further part in combustion. It is these partially combusted components that form smoke. The faster and more turbulent the reaction, the more likely that reaction components will be removed prior to complete combustion, hence the darker and thicker the smoke from a headfire, as opposed to the lighter, thinner smoke from a backing fire (Cheney and Sullivan, 1997).

Because the main source of heat into the combustion process comes from the exothermic reaction of the gas-phase products of levoglucosan and these products are buoyant and generally convected away from the solid fuel, the transport of the heat generated from these reactions is extremely complex and brings us to the physics of combustion.

Physics of combustion

The physics involved in the combustion of wildland fuel and the behaviour of wildland fires is, like the chemistry, complicated and highly dependent on the conditions in which a fire is burning. The primary physical process in a wildland fire is that of heat transfer. Williams (1982) gives nine possible mechanisms for the transfer of heat from a fire:

1. Diffusion of radicals

2. Heat conduction through a gas
3. Heat conduction through condensed materials
4. Convection through a gas
5. Liquid convection
6. Fuel deformation
7. Radiation from flames
8. Radiation from burning fuel surfaces
9. Firebrand transport.

1, 2 and 3 could be classed as diffusion at the molecular level. 4 and 5 are convection (although the presence of liquid phase fuel is extremely rare) but can be generalised to advection to include any transfer of heat through the motion of gases. 7 and 8 are radiation. 6 and 9 could be classed as solid fuel transport. This roughly translates to the three generally accepted forms of heat transfer (conduction, convection and radiation) plus solid fuel transport, which, as Emmons (1966) points out, is not trivial or unimportant in wildland fires.

The primary physical processes driving the transfer of heat in a wildland fire are that of advection and radiation. In low wind conditions, the dominating process is that of radiation (Weber, 1989). In conditions where wind is not insignificant, it is advection that dominates (Grishin et al., 1984). However, it is not reasonable to assume one works without the other and thus both mechanisms must be considered.

In attempting to represent the role of advection in wildland fire spread, the application of fluid dynamics is of prime importance. This assumes that the gas flow can be considered as a continuous medium or fluid.

Advection or Fluid transport

Fluid dynamics is a large area of active research and the basic outlines of the principles are given here. The interested reader is directed to a considerable number of texts on the subject for more in-depth discussion (e.g. Batchelor (1967); Turner (1973)).

The key aspect of fluid dynamics and its application to understanding the motion of gases is the notion of continuity. Here, the molecules or particles of a gas are considered to be *continuous* and thus behave as a fluid rather than a collection of particles. Another key aspect of fluid mechanics (and physics in general) is the fundamental notion of the conservation of quantities which is encompassed in the fluidised *equations of motion*.

A description of the rate of change of the density of particles in relation to the velocity of the particles and distribution of particles provides a method of describing the continuity of the particles. By taking the zeroth velocity moment of the density distribution (multiplying by \mathbf{u}^k (where $k = 0$, in this case) and integrating with respect to \mathbf{u}), the equation

of continuity is obtained. If the particles are considered to have mass, then the continuity equation also describes the conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (3)$$

where ρ is density, t is time, and \mathbf{u} is the fluid velocity (with vector components u , v , and w) and $\nabla \cdot$ is the Laplacian or gradient operator (i.e. in three dimensions $\mathbf{i} \frac{\partial}{\partial x} + \mathbf{j} \frac{\partial}{\partial y} + \mathbf{k} \frac{\partial}{\partial z}$). This is called the *fluidised* form of the continuity equation and is presented in the form of Euler's equations as a partial differential equation.

However, in order to solve this equation, the evolution of \mathbf{u} is needed. This incompleteness is known as the closure problem and is a characteristic of all the fluid equations of motion. The next order velocity moment ($k = 1$) can be taken and the evolution of the velocity field determined. This results in an equation for the force balance of the fluid or the *conservation of momentum* equation:

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}) \mathbf{u} + \nabla p = 0, \quad (4)$$

where p is pressure. However, the evolution of p is then needed to solve this equation. This can be determined by taking the second velocity moment ($k=2$) which provides an equation for the conservation of energy, but it itself needs a further, incomplete, equation to provide a solution. One can either continue determining higher order moments *ad nauseum* in order to provide a suitably approximate solution (as the series of equations can never be truly closed) or, as is more frequently done, utilise an equation of state to provide the closure mechanism. In fluid dynamics, the equation of state is generally that of the ideal gas law (e.g. $pV = nRT$). The above equations are in the form of the Euler equations and represent a simplified (inviscid) form of the Navier-Stokes equations.

Buoyancy, convection and turbulence

The action of heat release from the chemical reaction within the combustion zone results in heated gases, both in the form of combustion products as well ambient air heated by, or entrained into, the combustion products. The reduction in density caused by the heating of the gas increases the buoyancy of the gas and results in the gas rising as convection which can then lead to turbulence in the flow. Turbulence acts over the entire range of scales in the atmosphere, from the fine scale of flame to the atmospheric boundary layer, and acts to mix heated gases with ambient air and to mix the heated gases with unburnt solid phase fuels. It also acts to increase flame immersion of fuel. The action of turbulence also affects the transport of solid phase combustion, such as that of firebrands, resulting in spotfires downwind of the main burning front.

Suitably formulated Navier-Stokes equations can be used to incorporate the effects of buoyancy, convection and turbulence. However, these components of the flow can be investigated individually utilising particular approximations, such as Boussinesq's concept of eddy viscosity for the modelling of turbulence, or buoyancy as a renormalised variable

for modelling the effects of buoyancy. Specific methods for numerically solving turbulence within the realm of fluid dynamics, including renormalisation group theory (RNG) and large eddy simulation (LES), have been developed. Convective flows are generally solved within the broader context of the advection flow with a prescribed heat source.

Radiant heat transfer

Radiant heat is a form of electromagnetic radiation emitted from a hot source and is in the infra-red wavelength band. In flame, the primary source of the radiation is thermal emission from carbon particles, generally in the form of soot (Gaydon and Wolfhard, 1960), although band emission from electronic transitions in molecules also contributes to the overall radiation from a fire.

The general method of modelling radiant heat transfer is through the use of a radiant transfer equation (RTE) of which the simplest is that of the Stefan-Boltzmann equation:

$$q = \sigma T^4, \quad (5)$$

where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ J K}^{-4} \text{ m}^{-2} \text{ s}^{-1}$) and T is the radiating temperature of the surface (K). While it is possible to approximate the radiant heat flux from a fire as a surface emission from the flame face, this does not fully capture the volumetric emission nature of the flame (Sullivan et al., 2003) and can lead to inaccuracies in flux estimations if precise flame geometry (i.e. view factor), temperature and emissivity equivalents are not known.

More complex solutions of the RTE, such as treating the flame as a volume of radiation emitting, scattering and absorbing media, can improve the prediction of radiant heat but are necessarily more computationally intensive; varying levels of approximation (both physical and numerical) are frequently employed to improve the computational efficiency. The Discrete Transfer Radiation Model (DTRM) solves the radiative transfer equation throughout a domain by a method of ray tracing from surface elements on its boundaries and thus does not require information about the radiating volume itself. Discrete Ordinate Method (DOM) divides the volume into discrete volumes for which the full RTE is solved at each instance and the sum of radiation along all paths from an observer calculated. The Differential Approximation (or P1 method) solves the RTE as a diffusion equation which includes the effect of scattering but assumes the media is optically thick. Knowledge about the media's absorption, scattering, refractive index, path length and local temperature are required for many of these solutions. Descriptions of methods for solving these forms of the RTE are given in texts on radiant heat transfer (e.g. Drysdale (1985)). Sacadura (2005) and Goldstein et al. (2006) review the use of radiative heat transfer models in a wide range of applications.

Transmission of thermal radiation can be affected by smoke or band absorption by certain components of the atmosphere (e.g CO_2 , H_2O).

Firebrands (solid fuel transport)

Determination of the transport of solid fuel (i.e. firebrands), which leads to the initiation of spotfires downwind of the main fire front is highly probabilistic (Ellis, 2000) and not readily amenable to a purely deterministic description. This is due in part to the wide variation in firebrand sources and ignitions and the particular flight paths any firebrand might take. Maximum distance that a firebrand may be carried is determined by the intensity of the fire and the updraught velocity of the convection, the height at which the firebrand was sourced and the wind profile aloft (Albini, 1979; Ellis, 2000). Whether or not the firebrand lands alight and starts a spotfire is dependent upon the nature of the firebrand, how it was ignited, its combustion properties (including flaming lifetime) and the ignition properties of the fuel in which it lands (e.g. moisture content, bulk density, etc) (Plucinski, 2003).

Atmospheric interactions

The transport of the gas phase of the combustion products interacts with the atmosphere around it, transferring heat and energy, through convection and turbulence. The condition of the atmosphere, particularly the lapse rate, or the ease with which heated parcels of air rise within the atmosphere, controls the impact that buoyancy of the heated air from the combustion zone has on the atmosphere and the fire.

Changes in the ambient meteorological conditions, such as changes in wind speed and direction, moisture, temperature, lapse rates, etc, both at the surface and higher in the atmosphere, can have a significant impact on the state of the fuel (moisture content), the behaviour of a fire, its growth, and, in turn, the impact that fire can have on the atmosphere itself.

Topographic interactions

The topography in which a fire is burning also plays a part in the way in which energy is transferred to unburnt fuel and the ambient atmosphere. It has long been recognised that fires burn faster upslope than they do down, even with a downslope wind. This is thought to be due to increased transfer of radiant heat due to the change in the geometry between the fuel on the slope and the flame, however recent work (Wu et al., 2000) suggests that there is also increased advection in these cases.

Physical Models

This section briefly describes each of the physical models that were developed since 1990 (Table 3). Many are based on the same basic principles and differ only in the methodology of implementation or the purpose of use. They are presented in chronological order of first publication. Some have continued development, some have been implemented and tested against observations, others have not. Many are implemented in only one or two

dimensions in order to improve computational or analytical feasibility. Where information about the performance of the model on available computing hardware is available, this is given.

Weber (1991)

Weber's (1991b) model was an attempt to provide the framework necessary to build a physical model of fire spread through wildland fuel, rather than an attempt to actually build one. To that end, Weber highlights several possible approaches but does not give any definitive answer.

Weber begins with a reaction-transport formulation of the conservation of energy equation, which states that the rate of change of enthalpy per unit time is equal to the spatial variation of the flux of energy plus heat generation. He then formulates several components that contribute to the overall flux of energy, including radiation from flames, radiation transfer to fuel through the fuel, advection and diffusion of turbulent eddies. Heat is generated through a chemical reaction that is modelled by an Arrhenius law which includes heat of combustion.

This results in a first cut model that is one dimensional in x plus time. Advection, radiation and reaction components allow the evolution of the fluid velocity to be followed. Solid phase and gas phase fuel are treated separately due to different energy absorption characteristics.

In a more realistic version of this model, Weber treats the phase differences more explicitly, producing two coupled equations for the conservation of energy. The coupling comes from the fact that when the solid volatilises it releases flammable gas that then combusts, returning a portion of the released energy back to the solid for further volatilisation.

Weber determines that in two dimensions, the solution for the simple model is a two-dimensional travelling wave that produces two parametric equations for spatial x and y that yields an ellipse whose centre has been shifted. Weber favourably compares this result with that of Anderson et al. (1982), who first formalised the spread of a wildland fire perimeter as that of an expanding ellipse. No performance data are given.

AIOLOS-F (CINAR S.A., Greece)

AIOLOS-F was developed by CINAR S.A., Greece, as a decision support tool for wildland fire behaviour prediction. It is a computational fluid dynamics model that utilises the 3-dimensional form of the conservation laws to couple the combustion of a fuel layer with the atmosphere to model forest fire spread (Croba et al., 1994). It consists of two components, AIOLOS-T which predicts the local wind field and wind-fire interaction, and AILOS-F which models the fuel combustion.

The gas-phase conservation of mass equation is used to calculate the local wind perturbation potential, the gas-phase conservation of momentum is used to determine the vertical component of viscous flow, and a state equation to predict the air density and pressure change with air temperature (Lymberopoulos et al., 1998).

The combustion model is a 3D model of the evolution of enthalpy from which change in solid-phase temperature is determined. A thermal radiation heat transfer equation provides the radiant heat source term. Fuel combustion is modelled through a 3-dimensional fuel mixture-fraction evolution that is tied to a single Arrhenius Law for the consumption of solid phase fuel. The quantity of fuel consumed by the fire within a time interval is an exponential function of the mixture fraction.

The equations are solved iteratively and in precise order such that the wind field is solved first, the enthalpy, mixture-fraction, and temperature second. These are then used to determine the change in air density which is then fed back into the wind field equations taking into account the change in buoyancy due to the fire. The enthalpy, mixture-fraction and temperature are then updated with the new wind field. This is repeated until a solution converges, then the amount of fuel consumed for that time step is determined and the process continues for the next time step.

Fuel is assumed to be a single layer beneath the lowest atmosphere grid. Fuel is specified from satellite imagery on grids with a resolution in the order of 80 m. No data on calculation time is given, although it is described (Croba et al., 1994; Lymberopoulos et al., 1998) as being faster than real time.

FIRETEC (Los Alamos National Laboratory, USA)

FIRETEC (Linn, 1997), developed at the Los Alamos National Laboratory, USA, is a coupled multiphase transport/wildland fire model based on the principles of conservation of mass, momentum and energy. It is fully 3-dimensional and in combination with a hydrodynamics model called HIGRAD (Reisner et al., 1998, 2000a,b), which is used to solve equations of high gradient flow such as the motions of the local atmosphere, it employs a fully compressible gas transport formulation to represent the coupled interactions of the combustion, heat transfer and fluid mechanics involved in wildland fire (Linn et al., 2002b).

FIRETEC is described by the author as self-determining, by which it is meant that the model does not use prescribed or empirical relations in order to predict the spread and behaviour of wildland fires, relying solely on the formulations of the physics and chemistry to model the fire behaviour. The model utilises the finite volume method and the notion of a resolved volume to solve numerically its system of equations. It attempts to represent the average behaviour of the gases and solid fuels in the presence of a wildland fire. Many small-scale processes such as convective heat transfer between solids and gases are represented without each process actually being resolved in detail (Linn, 1997; Linn and Harlow, 1998a; Linn et al., 2002a). Fine scale wind patterns around structures smaller than the resolved scale of the model, including individual flames, are not represented explicitly.

The complex combustion reactions of a wildland fire are represented in FIRETEC using a few simplified models, including models for pyrolysis, char burning, hydrocarbon combustion and soot combustion in the presence of oxygen (Linn, 1997). Three idealised limiting cases were used as a basis for the original FIRETEC formulation:

1. gas-gas, with two reactants forming a single final product and no intermediate species.

2. gas-solid, being the burning of char in oxygen.

3. single reactant, being pyrolysis of wood.

However, Linn et al. (2002a) further refined this to a much simplified chemistry model that reduced the combustion to a single solid-gas phase reaction:



where N_{f,O_2} are the stoichiometric coefficients for fuel and oxygen. The equations for the evolution of the solid phase express the conservation of fuel, moisture and energy:

$$\frac{\partial \rho_f}{\partial t} = -N_f F_f \quad (7)$$

$$\frac{\partial \rho_w}{\partial t} = -F_w \quad (8)$$

$$(c_{pf}\rho_f + c_{pw}\rho_w)\frac{\partial T_s}{\partial t} = Q_{rad,s} + ha_v(T_g - T_s) - F_w(H_w + c_{pw}T_{vap}) + F(\Theta H_f + c_{pf}T_{pyr}N_f) \quad (9)$$

where $F_{f,w}$ are the reaction rates for solid fuel and liquid water depletion (i.e. the evaporation rate), $\rho_{f,w}$ are the solid phase (i.e. fuel and liquid water) density, Θ is the fraction of heat released from the solid-gas reaction and deposited back to the solid, $c_{pf,w}$ are the specific heats at constant pressure of the fuel and water, $T_{s,g}$ is the temperature of the solid or gas phase, T_{pyr} is the temperature at which the solid fuel begins to pyrolyse, $Q_{rad,g}$ is the net thermal radiation flux to the gas, h is the convective heat transfer coefficient, a_v is the ratio of solid fuel surface area to resolved volume, $H_{w,f}$ is the heat energy per unit mass associated with liquid water evaporation or solid-gas reaction (Eq. 6). It is assumed that the rates of exothermic reaction in areas of active burning are limited by the rate at which reactants can be brought together in their correct proportions (i.e. mixing limited). In a later work (Colman and Linn, 2003) a procedure to improve the combustion chemistry used in FIRETEC by utilising a non-local chemistry model in which the formation of char and tar are competing processes (as in for example, Fig. 2) is outlined. No results have been presented yet.

The gas phase equations utilise the forms of the conservation of mass, momentum, energy and species equations (Linn and Cunningham, 2005), similar to those of eqs (3 & 4), except that the conservation of mass is tied to the creation and consumption of solid and gas phase fuel, a turbulent Reynolds stress tensor and coefficient of drag for the solid fuel is included in the momentum equation, and a turbulent diffusion coefficient is included in the energy equation.

A unique aspect of the FIRETEC model is that the variables that occur in the relevant solid and gas phase conservation equations are divided into mean and fluctuating components and ensemble averages of the equations taken. This approach is similar to that used for the modelling of turbulence in flows.

The concept of a critical temperature within the resolved volume is used to initiate combustion and a probability distribution function based on the mean and fluctuating components of quantities in the resolved volume used to determine the mean temperature of the volume. Once the mean temperature exceeds the critical temperature, combustion commences and the evolution equations are used to track the solid and gas phase species. The critical temperature is chosen to be 500 K (Linn, 1997).

Turbulence in the flow around the combusting fuel is taken into account as the sum of three separate turbulence spectra corresponding to three cascading spatial scales, *viz.*: scale A, the scale of the largest fuel structure (i.e. a tree); scale B, the scale of the distance between fuel elements (i.e. branches); and scale C, the scale of the smallest fuel element (i.e. leaves, needles, etc) (Linn, 1997). In the original work modelling fire spread through a forest type, the characteristic scale lengths, s , for each scale were $s_A = 4.0$ m, $s_B = 2.0$ m and $s_C = 0.05$ m. By representing turbulence explicitly like this, the effect of diffusivity in the transfer of heat can be included.

The original version of FIRETEC did not explicitly include the effects of radiation, from either flame or fuel bed, or the absorption of radiation into unburnt fuel—primarily because flames and flame effects were at an unresolved scale within the model. As a result fires failed to propagate in zero wind situations or down slopes. Later revised versions (Bossert et al., 2000; Linn et al., 2001, 2002a) include some form of radiant transfer, however, this has not been formally presented anywhere and Linn et al. (2003) admits to the radiant heat transfer model being ‘very crude’.

Because FIRETEC models the conservation of mass, momentum and energy for both the gas and solid phases, it does have the potential, via the probability density function of temperature within a resolved volume, to track the probability fraction of mass in a debris-laden plume above the critical temperature (Linn and Harlow, 1998b) and thus provide a method of determining the occurrence of ‘spotting’ downwind of the main fire.

Running on a 128-node SGI computer with R10000 processors, a simplified FIRETEC simulation is described as running at ‘one to two orders of magnitude slower than realtime’ for a reasonable domain size (Hanson et al., 2000).

Forbes (1997)

Forbes (1997) developed a two dimensional model of fire spread utilising radiative heat transfer, species consumption and flammable gas production to explain why most fires don’t become major problems and why, when they do, they behave erratically. The basis for his model is observations of eucalypt forest fires which appeared either to burn quiescently or as raging infernos.

The main conceit behind the model is a two-path combustion model in which the solid fuel of eucalypt trees either thermally degrades directly and rapidly in an endothermic reaction, creating flammable fuel that then combusts exothermically, or produces flammable ‘eucalypt vapours’ endothermically which then combust exothermically.

Forbes developed a set of differential equations to describe this process and, because the reaction rates are temperature dependent, a temperature evolution for both the solid and gas phases, which are the sum of radiation, conduction (only included in the solid phase), convective heat loss, and the endothermic reaction losses in the production of the two competing flammable gases. Wind is included in the reaction equations.

Forbes concludes from his analysis of the one-dimensional form of the equations that a travelling wave solution is only sustainable if one of the two reaction schemes is endothermic overall and, since this won't be the case in a large, intense bushfire, that bushfires are unlikely to propagate as simple travelling waves. He determines a solution of a one-dimensional line fire but found that for most parameter values, the fire does not sustain itself. He found that the activation energies for each reaction, rate constants and heat release coefficients govern the propagation of the fire. Low activation energies and temperatures and high heat release rates are most likely to lead to growth of large fires.

Forbes then develops a two-dimensional solution for his equations, making the assumption that the height of the processes involved in the vertical direction (i.e. the flames) is small when compared to the area of the fire (i.e. by some orders of magnitude). This solution produces an elliptical fire shape stretched in the direction of the wind. He suggests improving the model by including fuel moisture. No performance data are given.

Grishin (Tomsk State University, Russia)

The work of AM Grishin has long been recognised for its comprehensive and innovative approach to the problem of developing physical models of forest fire behaviour (Weber, 1991b). While most of this work was conducted and published in Russia in the late 1970s and early 1980s, Grishin published a major monograph in 1992 that collected the considerable research he had conducted in one place, albeit in Russian. In 1997, this monograph was translated into English (Grishin, 1997) (edited by Frank Albini) and, for the first time, all of Grishin's work was available for English readers and is the main reason for the inclusion of his work in this review.

Grishin's model, as described in a number of papers (Grishin et al., 1983; Grishin, 1984; Grishin et al., 1984; Grishin and Shipulina, 2002), was based on analysis of experimental data and developed using the concepts and methods of reactive media mechanics. In this formulation, the wildland fuel (in this case, primarily forest canopy) and combustion products represent a non-deformable porous-dispersed medium (Grishin, 1997). Turbulent heat and mass transfer in the forest, as well as heat and mass exchange between the near-ground layer of the atmosphere and the forest canopy, are incorporated. The forest is considered as a multi-phase, multi-storied, spatially heterogeneous medium outside the fire zone. Inside the fire zone, the forest is considered to be a porous-dispersed, seven-phase, two-temperature, single-velocity, reactive medium. The six phases within the combustion zone are: dry organic matter, water in liquid state, solid products of fuel pyrolysis (char), ash, gas (composed of air, flying pyrolytic products and water vapour), and particles in the dispersed phase.

The model takes into account the basic physicochemical processes (heating, drying, pyrolysis of combustible forest material) and utilises the conservation of mass, momentum and energy in both the solid and gas phases. Other equations, in conjunction with initial and

boundary conditions, are used to determine the concentrations of gas phase components, radiation flux, convective heat transfer, and mass loss rates through Arrhenius rate laws using experimentally-determined activation energy and reaction rates. Grishin uses an effective reaction whose mass rate is close to that of CO to describe the combustion of ‘flying’ pyrolytic materials, because he determined that CO is the most common pyrolytic product (Grishin et al., 1983). Numerical analysis then enables the structure of the fire front and its development from initiation to be predicted. Versions of the full formulation of the multi-phase model are given in each of the works of Grishin (e.g. Grishin et al. (1983); Grishin (1997); Grishin and Shipulina (2002)).

While the model is formulated for three spatial dimensions plus time, the system of equations is generally reduced to a simpler form in which the vertical dimension is averaged over the height of the forest and the fire is assumed to be infinite in the y-direction, resulting in a one-dimensional plus time system of equations in which x is the direction of spread. The original formulation was intended only for the acceleration phase from ignition until steady state spread is achieved (Grishin et al., 1983). This was extended using a moving frame of reference and a steady-state rate of spread (ROS) to produce an analytical solution for the ROS which was found to vary linearly with wind speed (Grishin, 1984).

The speed of the fire front is taken to be the speed of the 700 K isotherm. The domain used for numerical analysis is in the order of 100-200 m long. Rate of spread is found to be dependent on initial moisture content of the fuel. No performance data are given.

IUSTI (Institut Universitaire des Systèmes Thermiques Industriels, France)

IUSTI (Larini et al., 1998; Porterie et al., 1998a,b, 2000) is based on macroscopic conservation equations obtained from local instantaneous forms (Larini et al., 1998) using an averaging method first introduced by Anderson and Jackson (1967). It aims to extend the modelling approach of Grishin et al. (1983) to thermal non-equilibrium flows. IUSTI considers wildland fire to be a multi-phase reactive and radiative flow through a heterogeneous combustible medium, utilising coupling through exchange terms of mass, momentum and energy between a single gas phase and any number of solid phases. The physico-chemical processes of fuel drying and pyrolysis due to thermal decomposition are modelled explicitly. Whereas FIRETEC was intended to be used to model wildland fire spread across large spatial scales, IUSTI concentrates on resolving the chemical and conservation equations at a much smaller spatial scale at the expense of 3-dimensional solutions. Thus, in its current formulation, IUSTI is 2-dimensional in the x and z directions.

Having derived the set of equations describing the general analysis of the reactive, radiative and multi-phase medium (Larini et al., 1998; Porterie et al., 1998a), the authors of IUSTI then reduced the system of equations to that of a much simplified version (called a zeroth order model) in which the effects of phenomena were dissociated from those of transfers. This was done by undertaking a series of simplifying assumptions. The first assumption was that solid particles are fixed in space, implying that solid phase momentum is nil; there is no surface regression and no char contribution in the conservation equations; and that the only combustion process is that of pyrolysis in the gaseous phase.

Mass loss rates are deduced from Arrhenius-type laws following on from the values used by Grishin et al. (1983) and Grishin (1997) and thermogravimetric analysis (Porterie et al., 2000). Mass rate equations for the conversion of solid fuel (gaseous production and solid fuel mass reduction) assume an independent reaction path between char formation and pyrolysis such that the rate of particle mass reduction relative to thermal decomposition of the solid phase and gas production rate is the sum of the all solid fuel mass loss rates due to water vaporisation, pyrolysis, char combustion (as a consequence of pyrolysis), and ash formation (as a consequence of char oxidation from the idealised reaction, $C + O_2 \rightarrow CO_2$). The model also includes a set of equations governed by the transition from the solid phase to a gas phase called the ‘jump’ condition because IUSTI considers such relatively small volumes. The pyrolysis products are assumed to be removed out of the solid instantaneously upon release. Mass diffusion of any chemical species is neglected and no chemical reactions occur in the solid phase. A single one-step reaction model in which fuel reacts with oxidant to produce product is implemented.

A later version of IUSTI (Porterie et al., 2000) utilises the density-weighted or Favre average form of the conservation equations due to the density variations caused by the heat release. The time-averaged, density-weighted (Favre) fluctuation of turbulent flux is approximated from Boussinesq’s eddy viscosity concept and the turbulent kinetic energy, κ , and dissipation rate, ϵ , are obtained from the renormalisation group theory (RNG).

The formation of soot is modelled as the soot volume fraction which forms mostly as a result of the pyrolysis process and so is assumed to be a percentage of the mass loss rate due to pyrolysis. The radiative transfer equation is based upon the mole fraction of the combustion products and the average soot volume fraction, treating the gas as gray.

Drag is included through the drag coefficient which is a function of the Reynolds number of the solid phase. Solid phase particles are treated as spheres. The conductive/convective heat transfer coefficient is expressed using the Reynolds number for flow around cylinders.

The governing equations of conservation in both gas and solid phases are discretised on a non-uniform grid using a finite-volume scheme. The domain over which the equations are solved is in the order of 1-2 m long by 0.1 m with an average resolution of $\simeq 0.01$ m.

A one-dimensional version of this model was constructed in an attempt to simplify the model (Morvan and Larini, 2001). A numerical experiment replicating fire spread through a tube containing pine needles (in order to replicate one-dimensional spread experimentally) was conducted. Results showed a linear increase in ROS with increasing wind speed up to a value of 16 cm s^{-1} . Beyond this value, ROS dropped off dramatically and pyrolysis flow rate reduced. Analysis of the species composition mass fractions showed that below 16 cm s^{-1} , the combustion is oxygen limited and is akin to smouldering combustion. Above 16 cm s^{-1} , the combustion became fuel-limited as the increased air flow increased convective cooling and slowed pyrolysis and hence ROS.

No performance data are given.

PIF97

The detailed work of Larini et al. (1998), Porterie et al. (1998a) and Porterie et al. (2000) provided the framework for the development of a related model, named PIF97 by its

authors (Dupuy and Larini, 1999; Morvan and Dupuy, 2001). The aim of this work was to simplify the multi-phase IUSTI model of Larini et al. (1998) and Porterie et al. (1998a) in order to develop a more operationally-feasible model of wildland fire spread. The full 2D IUSTI was reduced to a quasi-two-dimensional version in which the fuel bed is considered to be one-dimensional and the gas interactions (including radiation and convective mixing above the bed) are two dimensional (x and z). In a manner similar to IUSTU, two phases of media are considered—gas and solid. However, PIF97 assumes that the solid is homogeneous, unlike IUSTI which considers multiple solid phases.

PIF97 comes in two parts. The first is a combustion zone model that considers the radiative and convective heat transferred to the fuel bed in front of the flaming zone. The radiative component considers radiation flux from adjacent fuels, the ignition interface, flame and the ambient media surrounding the fuel. Radiation from solids is assumed to be blackbody at a temperature of 1123K. This value was selected so that the model could predict the spread of a single experimental fire in pinaster needles. Convective heat exchange depends on the Nusselt number which is approximated through a relation with the Reynolds number for the type of flow the authors envisage. This in turn relies on the assumption of flow around a cylinder of infinite length. Mass transfer and drag forces are similarly derived using approximations to published models and empirical correlations (i.e. assuming cylindrical particles). An ignition temperature for solid fuel of 600 K is used.

The second part of the model is the fire-induced flow in the flaming combustion zone behind the ignition interface. This depends on the ROS of the interface derived from the combustion part of the model. The temperature of this gas is assumed to be fixed at 900K. Other values between 750K and 1050K were investigated but no significant difference in results was found.

The numerical solution of PIF97 is based on a domain that is 25 cm long and uses a spatial resolution of 1 mm. Results of the model are compared to experimental results presented by Dupuy (2000) in which two radiation-only models, that of de Mestre et al. (1989) and a one-dimensional version of Albini (1985, 1986) were compared to laboratory experiments conducted with *Pinus pinaster* and *P. halipensis* needles. PIF97 was found to be comparable to the Albini model, except in *P. halipensis* needles where it performed markedly better. However, no model was found to ‘perform well’ in conditions of wind and slope.

A later version of PIF97 (Morvan and Dupuy, 2004) was extended to multiple solid phases in order to simulate Mediterranean fuel complexes comprising live and dead components of shrub and grass species, including twigs and foliage. An empirical correlation is used for the drag coefficient based on regular shapes (i.e. cylinder, sphere, etc.) A RNG $\kappa - \epsilon$ turbulence model using turbulent diffusion coefficients is incorporated and a pressure correction algorithm used to couple the pressure with the velocity.

The revised model was implemented as a 2D vertical slice through the fire front as a compromise between the computational time and need to study the main physical mechanisms of the fire propagation. 80×45 control volumes, each $10 \text{ cm} \times 3 \text{ cm}$ were used, defining a domain 8 m by 1.35 m. ROS was defined as the movement of the 500K isotherm inside the pyrolysis front. ROS was compared to other models and observations of shrub fires (Fernandes, 2001) and did not perform well. The authors summarise their model

as producing a ROS relationship for wind $< 3 \text{ m s}^{-1}$ as ‘an increasing function of wind speed’ and then say the ROS reaches a limiting value at a wind speed of about 5 m s^{-1} . The other models and observations showed either linear or power law ($\text{exp} < 1.0$) relationships.

Dupuy and Morvan (2005) added a crown layer to this model resulting in six families of solid phase fuel: three for shrubs (leaves and two size classes of twigs (0-2, 2-6 mm), one for grass, and two for the overstorey *P. halepensis* canopy (needles and twigs 2-6 mm). This version implemented a combustion model based on Arrhenius-type laws after Grishin (1997). Soot production (for the radiation transfer) was assumed at 5% of the rate of solid fuel pyrolysis.

The domain was $200 \text{ m} \times 50 \text{ m}$ high with, at its finest scale, cells $0.25 \text{ m} \times 0.025 \text{ m}$, average of 0.25×0.25 and largest $1.0 \times 0.25 \text{ m}$. 200 s of simulation took 48 hours on an Intel Pentium P4 2GHz machine.

LEMTA (Laboratoire d’Énergétique et de Mécanique Théorique et Appliquée, France)

This comprehensive model, developed by Sero-Guillaume and Margerit (2002) of Laboratoire d’Énergétique et de Mécanique Théorique et Appliquée in France, considers a two-phase model, gas and solid, in three regions of a forest—above the forest, in the forest and below the ground—at three scales: microscopic (plant cell solid/gas level), mesoscopic (branch and leaf level) and macroscopic (forest canopy/atmosphere level). They identify but do not investigate a fourth scale, that of the ‘gigascope’ or landscape level.

The combustion chemistry is simplified in that only gas-phase combustion is allowed. Solid phase chemistry only considers pyrolysis to gas-phase volatile fuel, char and tar. Soot production is not considered, nor is char combustion. Gas phases include O_2 , water, N_2 , fuel and inert residue. Solid to gas phase transitions are handled by interface jump relations.

Conservation of species mass, momentum and energy are derived for mesoscopic gas and solid phase interactions. These are then averaged over the larger macroscopic scale by using distribution theory and convoluting the equations to macroscopic quantities. Extended irreversible thermodynamics is then used to close the system of equations. Arguments about thermal equilibrium are used to further reduce the non-equilibrium equations for temperature and pressure.

The system of equations are then further simplified using assumptions about the nature of the fuel (at rest) and the size and interaction of the fuel particles with the gas phase (i.e. no advection, pressure or porosity variations in the solid phase). Drag is not included. Gas phase equations in the region above the forest do not include solid phase particles and, since soot is not modeled, cannot suitably describe radiant heat from flames.

Margerit and Sero-Guillaume (2002) and Chetehouna et al. (2004) reduced Sero-Guillaume and Margerit (2002) to two dimensions in order to produce a more operationally-feasible fire spread model. Margerit and Sero-Guillaume (2002) achieved this through assumptions that the scale of the fuel to the fire was such that the fuel could be considered a boundary layer and

the fire a one-dimensional interface between burning and unburnt fuel on the surface. (i.e. the fuel is thin relative to the width of the fire). A few assumptions are then made: there is no vertical component in the wind, the solid and gas phases are in thermal equilibrium, and the non-local external radiative heat flux is blackbody. The resulting two-dimensional model is a reaction-diffusion model similar in form to Weber (1991b). Assumptions about the speed of chemical reactions are made to get the pyrolysis occurring at an ignition temperature.

Chetehouna et al. (2004) further reduced the two-dimensional reaction-diffusion equations of Margerit and Sero-Guillaume (2002) by making some simplifying assumptions about the evaporation and ignition of the solid phase fuel. Here, fixed temperatures are used, 100 and 300°C respectively. Five distinct heating stages are used, each separated by the temperature of the fuel: 1) fuel heating to 100°C; 2) moisture evaporation at 100°C; 3) fuel heating to ignition temperature; 4) combustion at 300°C; and 5) mass loss due to chemical reactions and heat loss at flame extinction.

Separate equations with different boundary conditions are used for each stage but only stages 1-3 are important for fire spread. The equations for these stages are then non-dimensionalised and a limiting parameter, the thermal conductivity in the solid phase, is used as a parameter for variation. The equations are then solved as an eigenvalue problem in order to determine the ROS for each stage. Two flame radiation models are used to incorporate long distance radiant heat flux from flames: de Mestre et al. (1989) and the version given by Margerit and Sero-Guillaume (2002). Rates of spread are similar for both flame models and reduce with increasing thermal conductivity. However, despite the fact that the authors say the models compare well with experimental results, no results or comparisons are given.

The model is then simulated on a computer. It provides a circular shape in no wind/no slope, and an elongated shape under wind. An example burning in real terrain is shown but no discussion of its performance against real fires is given. Mention is made of it operating in real-time on a PC.

UoS (University of Salamanca, Spain)

Asensio and Ferragut (2002) constructed a 2D model of fire spread that used radiation as the primary mode of heat transfer but also incorporated advection of hot gas and convective cooling of fuels. The model, described here as UoS, employed a simplified combustion chemistry model (only two phases: gas and solid, and two species: fuel and oxygen) and utilised only conservation of energy and species mass. It is assumed combustion is fuel limited and thus only one species is conserved. Arrhenius laws for fuel consumption are used. Turbulence is not accounted for directly or explicitly, but a term for advection with a wind velocity vector is included.

The model is of a form that explicitly includes convective heating, radiation, chemical energy release and natural convection. Non-dimensionalised forms of the system of equations are then discretised into a finite element form for numerical computation. The model is considered to be a first step and the authors aim to link it to the Navier-Stokes equations for better incorporation of turbulence.

Asensio et al. (2005) attempted to provide a link from the 2D surface fire spread of UoS to a model of convection above the fire. The model starts with the conservation of momentum equation and then makes hydrostatic assumptions about the atmosphere. It then decomposes this 3D model into a 2D model with height that is averaged over a layer of fixed thickness. An asymptotic model is then formed and solved producing 2D streamfunctions and an equation for the velocity on the surface (which can then be inserted directly into the original spread model for the advection of heat around the fire).

No performance data are given.

WFDS (National Institute of Safety Technology, USA)

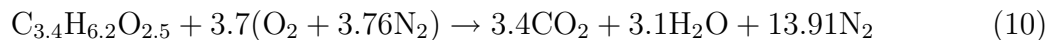
The Wildland Fire Dynamic Simulator (WFDS), developed by the US National Institute of Safety Technology (Mell et al., 2006), is an extension of the model developed to predict the spread of fire within structures, Fire Dynamic Simulator (FDS). This model is fully 3D, is based upon a unique formulation of the equations of motion for buoyant flow (Rehm and Baum, 1978) and is intended for use in predicting the behaviour of fires burning through peri-urban/wildlands (what the authors call ‘Community-scale fire spread’ (Rehm et al., 2003; Evans et al., 2003)). The main objective of this model is to predict the progress of fire through predominantly wildland fuel augmented by the presence of combustible structures.

WFDS utilises a varying computational grid to resolve volumes as low as 1.6 m (x) \times 1.6 m (y) \times 1.4 m (z) within a simulation domain in the order of 1.5 km² in area and 200 m high. Outside regions of interest, the grid resolution is decreased to improve computation efficiency.

Mell et al. (2006) give a detailed description of the WFDS formulated for the specific initial case of grassland fuels, in which vegetation is not resolved in the gas-phase (atmosphere) grid but in a separate solid fuel (surface) grid (which the authors admit is not suitable for fuels in which there is significant vertical flame spread and air flow through the fuel). In the case presented, the model includes features such as momentum drag caused by the presence of the grass fuel (modelled as cylinders) which changes over time as the fuel is consumed. Mechanical turbulence, through the dynamic viscosity of the flow through the fuel, is modelled as a subgrid parameter via a variant of the Large Eddy Simulation (LES) method.

The WFDS assumes a two-stage endothermic thermal decomposition (water evaporation and then solid fuel ‘pyrolysis’). It uses the temperature dependent mass loss rate expression of Morvan and Dupuy (2004) to model the solid fuel degradation and assumes that pyrolysis occurs at 127°C. Solid fuel is represented as a series of layers which are consumed from the top down until the solid mass reaches a predetermined char fraction at which point the fuel is considered consumed.

WFDS assumes combustion occurs solely as the result of fuel gas and oxygen mixing in stoichiometric proportion (and thus is independent of temperature). Char oxidation is not accounted for. The gas phase combustion is modelled using the following stoichiometric relation:



Due to the relatively coarse scale of the resolved computation grids within WFDS, detailed chemical kinetics are not modelled. Instead, the concept of a mixture fraction within a resolved volume is used to represent the mass ratio of gas-phase fuel to oxygen using a fast chemistry or flame sheet model which then provides the mass loss flux for each species. The energy release associated with chemical reactions is not explicitly presented but is accounted for by an enthalpy variable as a function of species. The model assumes that the time scale of the chemical reactions is much shorter than that of mixing.

Thermal radiation transport assumes a gray gas absorber-emitter using the P1 radiation model for which the absorption coefficient is a function of the mixture fraction and temperature for a given mixture of species. A soot production model is not used; instead it is an assumed fraction of the mass of fuel gas consumed.

Mell et al. (2006) provides simulation information for two experimental grassfires. In the first case, a high intensity fire in a plot $200\text{ m} \times 200\text{ m}$ within a domain of $1.5\text{ km} \times 1.5\text{ km}$ and vertical height of 200 m for a total 16 million grid cells, the model, running on 11 processors, took 44 cpu hours for 100 s of simulated time. Another lower intensity experiment over a similar domain took 25 cpu hours for 100 s of simulated time.

Quasi-physical models

This section briefly describes quasi-physical models that have appeared in the literature since 1990 (de Mestre et al. (1989) is included because it was missed by previous reviews and provides the basis for a subsequent model).

The main feature of this form of model is the lack of combustion chemistry and reliance upon the transfer of a prescribed heat release (i.e. flame geometry and temperature are generally assumed). They are presented in chronological order of publication (Table 4).

Australian Defence Force Academy (ADFA) I, Australia

de Mestre et al. (1989) of the Australian Defence Force Academy, University of New South Wales, developed a physical model of fire spread based initially only on radiative effects, in much the same manner as that of Albin (1985, 1986) (see below) but in a much simplified manner.

The authors utilise a conservation of heat approach to model the spread of a planar fire of infinite width across the surface of a semi-transparent fuel bed in a no wind, no slope situation. However, unlike Albin, who modelled the fuel bed in two dimensions (i.e., x and z), de Mestre et al. (1989) chose to model only the top of the fuel bed, arguing that it is this component of the fuel bed that burns first before burning down into the bed; thus this model is one dimensional plus time.

Assumptions include vertical flames that radiate as an opaque surface of fixed temperature and emissivity, a fixed fuel ignition temperature, and radiation from the combustion zone as an opaque surface of fixed temperature and emissivity. Here they also assume that the

ignition interface in the fuel bed is a linear surface, as opposed to Albini’s curved one, in order to simplify the computations.

Two approaches to the vaporisation of the fuel moisture are modelled—one in which it all boils off at 373 K (i.e. 3 phase model (<373 K, 373 K, >373 K)) and one in which it boils off gradually below 373 K (2 phase model (≤ 373 K, > 373 K)).

The final model includes terms for radiation from flame, radiation from combustion zone, radiative cooling from solid fuel, and convective cooling from solid fuel. Without the cooling terms, the model was found to over-predict ROS by a factor of 13. A radiative cooling factor brought the over-prediction down to a factor of 9. Including a convective cooling term to the ambient air apparently brought the prediction down to the observed ROS but this was not detailed.

No performance data are given.

TRW, USA

Carrier et al. (1991) introduced an analytical model of fire spread through an array of sticks in a wind tunnel (called here TRW). Unlike many preceding fire modelling attempts, they did not assume that the dominant preheating mechanism is radiation, but a mixture of convective/diffusive (what they called ‘confusive’) heating.

Predominately concerned with deriving a formula for the forward spread of the fire interface in the wind tunnel (based on a series of experiments conducted and reported by Wolff et al. (1991)), Carrier et al. (1991) assumed that the fire achieves a ‘quasi-steady’ ROS in conditions of constant wind speed and fuel conditions. They make the point that, at the scale they are looking at, the spread can be viewed as continuous and can thus involve a catch-all heat transfer mechanism (gas-phase diffusion flame) in which radiation plays no part and it is the advection of hot gas from the burned area that preheats the fuel (assuming all of it is burnt).

The model is two-dimensional in the plane XY in which it is assumed there is no lateral difference in the spread of the fire (which is different to assuming an infinite width fire). Indeed, their formulation actually needs the width of the fuel bed *and* the width of the wind tunnel. The fluctuating scale of the turbulence within the tunnel is incorporated in a scale length parameter. Air flow within the fuel bed is ignored.

Using a first-principles competing argument, they say that if radiation was to be the source of preheating, the estimate of radiant energy (2.9 J/g) ahead of the fire falls well short of the 250 J/g required for pyrolysis. A square root relation between wind speed normalised by fuel load consumed and rate of forward spread was determined and supported by experimental observation (Wolff et al., 1991). Carrier et al. (1991) suggest that only when fuel loading is very high (on the order of 2 kg m^{-2}) will radiative preheating play a role comparable to that of convective/diffusive preheating.

No performance data are given.

Albini, USA

Albini (1985, 1986) developed a two-dimensional (XZ) quasi-physical radiative model of fire spread through a single homogeneous fuel layer. The latter paper improved upon the former by including a fuel convective cooling term. Both models required that flame geometry and radiative properties (temperature and emissive power) be prescribed *a priori* in order for the model to then determine, in an iterative process, the steady-state speed of the fire front. The fire front is considered to be the isothermal flame ignition interface between unburnt and burnt fuel expressed as an eigenvalue problem, utilising a 3-stage fuel heating model ($<373\text{ K}$, 373 K , $373\text{ K} \leq T_i$), where T_i is the ignition temperature of 700 K .

A modified version of this spread model, in which a thermally-inert zone that allowed the passage of a planar flame front but did not influence the spread process was placed beneath the homogeneous fuel layer to simulate propagation of a fire through the tree crowns, was tested against a series of field-based experimental crown fires conducted in immature Jack Pine (Albini and Stocks, 1986). The results from one experimental fire were used to parameterise the model (flame radiometric temperature and free flame radiation) and obtain flame geometry and radiative properties for the remaining fires. The model was found to perform reasonably well, with a maximum absolute percent error of 14%.

Albini (1996) extended the representation of the fuel to multiple levels, where surface fuel, sub-canopy fuel and the canopy fuel are incorporated into the spread model. Albini also introduced a closure mechanism for removing the requirement for flame geometry and radiative properties to be given *a priori*. The former transcribed the fuel complex into a vertical series of equivalent single-component (homogeneous) surrogate layers based on weighted contributions from different fuel components (e.g. surface-volume ratio, packing ratio, etc.) within a layer.

The closure method involves the positing of a ‘trial’ rate of spread, along with free flame geometry and ignition interface shape, that are then used to predict a temperature distribution within the fuel. This distribution is then subsequently used in a sub-model to refine the fire intensity, rate of spread, flame geometry, etc. This continues iteratively until a convergence of results is achieved. A quasi-steady ROS is assumed and the temperature distribution is assumed stationary in time. A conservation of energy argument, that the ROS will yield a fire intensity that results in a flame structure that will cause that ROS, is then used to check the validity of the final solution.

Butler et al. (2004) used the heat transfer model of Albini (1996) in conjunction with models for fuel consumption, wind velocity profile and flame structure, to develop a numerical model for the prediction of spread rate and fireline intensity of high intensity crown fires. The model was found to accurately predict the relative response of fire spread rate to fuel and environment variables but significantly over-predicted the magnitude of the speed, in one case by a factor of 3.5. No performance data are given.

University of Corsica (UC), France

The University of Corsica undertook a concerted effort to develop a physical model of fire spread (called here UC) that would be suitable for faster than real-time operational

use. The initial approach (Santoni and Balbi, 1998a,b; Balbi et al., 1999) was a quasi-physical model in which the main heat transfer mechanisms were combined into a so-called ‘reactive diffusion’ model, the parameters of which were determined experimentally.

The main components of UC are a thermal balance model that incorporates the combined diffusion of heat from the three mechanisms and a diffusion flame model for determination of radiant heat from flames. The heat balance considers: heat exchanged with the air around a fuel cell, heat exchanged with the cell’s neighbours, and heat released by the cell during combustion. It is assumed that the rate of energy release is proportional to the fuel consumed and that the fuel is consumed exponentially. The model is two-dimensional in the fuel layer (the plane XY). No convection, apart from convective cooling to neighbouring cells is taken into account, nor is turbulence. The model assumes that all combustion follows one path. Model parameters were determined from laboratory experiments.

Initially, radiation from the flame was assumed to occur as surface emission from a flame of height, angle and length computed from the model and an isothermal of 500K. Flame emissivity and fuel absorptivity were determined from laboratory experiments in a combined parameter. The early version of the model was one dimensional for the fuel bed and two dimensional (x and z) for flame. Forms of the conservation of mass and momentum equations are used to control variables such as gas velocity, enthalpy, pressure and mass fractions.

Santoni et al. (1999) presented a 2D version of the model in which the radiative heat transfer component was reformulated such that the view factor, emissivity and absorptivity were parameterised with a single value for each fuel and slope combination that was derived from laboratory experiments. This version was compared to experimental observations (Dupuy, 1995) and the radiation-only models of Albini (1985, 1986) and de Mestre et al. (1989) (Morandini et al., 2000). It was found to predict the experimental increase in ROS with increasing fuel load much better than the other models. The UC model also outperformed the other models on slopes but this is not surprising as it had to be parameterised for each particular slope case.

Simeoni et al. (2001a) acknowledged the inadequacies of the initial ‘reaction-diffusion’ model and Simeoni et al. (2001a,b, 2002, 2003) undertook to improve the advection component of the UC model by reducing the physical modelling of the advection component of the work of Larini et al. (1998) and Porterie et al. (1998a,b) to two dimensions to link it to the UC model. It occurred in two parts: one as a conservation of momentum component that is included in the thermal balance equations (temperature evolution), and one as a velocity profile through the flaming zone. They assumed that buoyancy, drag and vertical variation are equivalent to a force proportional to the quantity of gas in the multi-phase volume and that all the forces are constant whatever the gas velocity. The net effect is that the horizontal velocity decreases through the flame to zero at the ignition interface and does not change with time. Again, the quasi-physical model was parameterised using a temperature-time curve from a laboratory experiment with no wind or slope. The modified model improves the performance only marginally, particularly in the no slope case but still underpredicts ROS.

The original UC model included only the thermal balance with a diffusion term encompassing convection, conduction and radiation. The inclusion of only short distance radiation

interaction failed to properly model the pre-heating of fuel due to radiation prior to the arrival of the fire front. Morandini et al. (2001a,b, 2002) attempted to address this issue by improving the radiant heat transfer mechanism of the model. Surface emission from a vertical flame under no wind conditions is assumed and a flame tilt factor is included when under the influence of wind. The radiation transfer is based on the Stefan-Boltzmann radiation transfer equation where the view factor from the flame is simplified to the sum of vertical panels of given width. The length of each panel is assumed to be equal to the flame depth, mainly because flame height is not modelled.

In cases of combined slope and wind, it was assumed that the effects on flame angle are independent of slope. Morandini et al. (2002) approximate the effects of wind speed by an increase in flame angle in a manner similar to terrain slope by taking the inverse tangent of the flame angle of a series of experiments divided into the mid-flame wind speed. This is then considered a constant for a range of wind speeds and slopes. Again, the model is parameterised using a laboratory experiment in no-wind, no slope conditions.

Results are given for a range of slopes (-15 to $+15^\circ$) and wind speeds ($1, 2, 3 \text{ m s}^{-1}$). The prediction in no wind and slope is good, as are the predictions for wind and no slope. The model breaks down when slope is added to high wind (i.e. 3 m s^{-1}). Here, however, they determine that their model only works for equivalent flame tilt angles (i.e. slope and wind angles) up to 40 degrees.

The model is computed on a fine-scale non-uniform grid using the same methods as Larini et al. (1998). In this case the smallest resolution is 1 cm^3 and 0.1 seconds. On a Sun Ultra II, the model took 114 s to compute 144 s of simulation. When the domain is reduced to just the fire itself, the time reduced to 18 s.

ADFA II, Aust/USA

Catchpole et al. (2002) introduced a much refined and developed version of ADFA (de Mestre et al., 1989), here called ADFA II. Like ADFA I, it is a heat balance model of a fuel element located at the top of the fuel bed. The overall structure of the model is the same, with radiative heating and cooling of the fuel (from both the flames and the combustion zone), and convective heating and cooling. It is assumed that the flame emits as a surface and they use laboratory experiments to determine the emissive energy flux based on a Gaussian vertical flame profile and a maximum flame radiant intensity. It assumes infinite width for the radiative emissions.

Combustion zone radiation is treated similarly. Byram's convective number (Byram, 1959b) and fireline intensity (Byram, 1959a) are used to determine flame characteristics (angle, height, length, etc). Empirical models are used to determine gas temperature profile above and within the fuel as well as maximum gas temperature, etc. ADFA II utilises an iterative method to determine ROS, similar to that of Albin (1996), assuming that the fire is at a steady-state rate of spread.

No performance data are given.

Coimbra (2004)

The aim of Vaz et al. (2004) was not to develop a new model of fire spread as such, but to combine the wide range of existing models in such a way as to create a seamless modular quasi-physical model of fire spread that can be tailor-made for particular situations by picking and choosing appropriate sub-models. The ‘library’ of models from which the authors pick and choose their sub-models are classified as: heat sink models (including Rothermel (1972); Albini (1985, 1986); de Mestre et al. (1989)), which consider the conservation of energy aspects of fuel heating and moisture loss and ignition criteria; heat flux models (including Albini (1985, 1986); Van Wagner (1967)), which consider the net exchange of radiative energy between fuel particles; and heat source models (including Thomas (1967, 1971)), that consider the generation of energy within the combustion zone and provide closure for the other two types of models.

The authors compared a fixed selection of sub-models against data gathered from a laboratory experiment conducted on a fuel bed 2 m wide by 0.8 m long under conditions of no wind and no slope. The set of models was found to underpredict ROS by 46%. This was improved to 6% when observed flame height was used in the prediction. Predicted flame height, upon which several of the sub-models depend directly, did not correspond with observations, regardless of the combination of sub-models selected. Rather than producing a fire behaviour prediction system that utilises the best aspects of its component models, the result appears to compound the inadequacies of each of the sub-models. None of the three classes of sub-models consider advection of hot gases in the heat transfer.

Discussion and summary

The most distinguishing feature of a fully physical model of fire spread in comparison with one that is described as being quasi-physical is the presence of some form of combustion chemistry. These models determine the energy released from the fuel, and thus the amount of energy to be subsequently transferred to surrounding unburnt fuel and the atmosphere, etc., from a model of the fundamental chemistry of the fuel and its combustion. Quasi-physical models, on the other hand, rely upon a higher level model to determine the magnitude of energy to be transferred and generally require flame characteristics to be known *a priori*.

Physical models themselves can be divided primarily into two streams; those that are intended for operational or experimental use (or at least field validation) and those that are purely academic exercises. The latter are characterised by the lack of follow-up work (e.g. Weber, Forbes, UoS), although it is possible that components of such models may later find their way into models intended for operational or experimental use. Sometimes the nature of the model itself dictates its uses, rather than the authors’ intention. Grishin, IUSTI, and LEMTA were all formulated with the intention of being useful models of fire spread but either due to the complex nature of the models, the reduced physical dimensionality of the model or the restricted domain over which the model can operate feasibly, the model has not and most probably will not be used operationally.

The remaining physical models, AIOLOS-F, FIRETEC, PIF97 and WFDS have all had extended and ongoing development and each are capable of modelling the behaviour of

a wildland fire of landscape scale (i.e. computational domains in excess of $\simeq 100$ m. However, in the effort to make this computationally feasible, each model significantly reduces both the resolution of the computational domain and the precision of the physical models implemented.

Each of these remaining physical models is also different from the others in that efforts to conduct validation of their performance against large scale wildland fires have been attempted. Difficulties abound in this endeavour. As is the case with any field experiment, it is very difficult to measure all required quantities to the degree of precision and accuracy required by the models. In the case of wildland fires, this difficulty is increased by two or three orders of magnitude. Boundary conditions are rarely known and other quantities are almost never measured at the site of the fire itself. Mapping of the spread of wildland fires is haphazard and highly subjective.

IUSTI and PIF97 undertook validation utilising laboratory experiments of suitable spatial scales in which the number and type of variables were strictly controlled. In many laboratory experiments, the standard condition is one of no wind and no slope. While wildland fires in flat terrain do occur, it is very rare (if not impossible) for these fires to occur in no wind. The ability to correctly model the behaviour of a fire in such conditions is only one step in the testing of the model. Both IUSTI and PIF97 (as well as a number of the quasi-physical models discussed here) were found wanting in conditions of wind and/or slope.

Morvan et al. (2004) argues that purely theoretical modelling with no regard for field observations is of less use than a field-based model for one particular set of circumstances. Validation against fire behaviour observed in artificial fuel beds under artificial conditions is only half the test of the worth of a model. The importance of comparison against field observation is not to be understated. For regardless of the conditions under which a field experiment (i.e. an experimental fire carried out in naturally occurring, albeit modified, conditions) is conducted, it is the real deal in terms of wildland fire behaviour and thus provides the complete set of interactions between fire, fuel, atmosphere and topography. Both Linn and Cunningham (2005) and Mell et al. (2006) identified significant deficiencies within their models (FIRETEC and WFDS, respectively) that only comparison against field observations could have revealed.

Both FIRETEC and WFDS attempted validation against large scale experimental grassland fires (Cheney et al., 1993) and thus avoided many of the issues of validation against wildfire observations. However, the issue of identifying the source of discrepancy in such complex models is just as difficult as obtaining suitable data against which to test the model.

Computationally feasible models can be either constructed from simple models or reduced from complete models (Sero-Guillaume and Margerit, 2002) and each of the preceding physical models are very much in the latter category. Quasi-physical models are very much of the former but suffer from the same difficulties in validation against large scale fires. Of the quasi-physical models discussed here, only those of Albin have been tested against wildland fires, the others against laboratory experimental fires.

However, being constructed from simple models may make the quasi-physical models less complex but does not necessarily make them any more computationally feasible. Table 5 shows a summary of the scope, resolution and computation time available in the literature

for each of the models. Not all models have such information, concentrating primarily on the underlying basis of the models rather than their computational feasibility. But for those models whose *raison de tre* is to be used actively for fire management purposes, computational feasibility is of prime concern. Here models such as AIOLOS-F, FIRETEC, WFDS and UC stand out from the others because of their stated aim to be a useful tool in fire management.

PIF97, WFDS and UC all give nominal computation times for a given period of simulation. Only UC, being a quasi-physical model reduced from a more fundamental model is better than realtime. PIF97 and WFDS, using the current level of hardware, are all much greater than realtime (in the order of 450 times realtime for WFDS on 11 processors (Mell et al., 2006)). FIRETEC is described as being ‘several orders of magnitude slower than realtime’. FIRETEC, WFDS and UoS are significantly different from the other physical models (and most of the quasi-physical models for that matter) in that their resolutions are significantly larger (in some cases by two orders of magnitude). However, the time step used by FIRETEC (0.002 s) in the example given, means that the gains to be made by averaging the computations over a larger volume are lost in using a very short time interval.

The authors of FIRETEC are resolved to not being able to predict the behaviour of landscape wildland fires and suggest that the primary use of purely physical models of fire behaviour is the study of fires under a variety of conditions in a range of fuels and topographies in scenarios that are not amenable to field experimentation. This is a laudable aim, and in an increasingly litigious social and political environment, may be the only way to study large scale fire behaviour in the future, but this assumes that the physical model is complete, correct, validated and verified. Hanson et al. (2000) suggest that the operational fire behaviour models of the future will be reduced versions of the purely physical models being developed today.

It is obvious from the performance data volunteered in the literature, that the current approaches to modelling fire behaviour *on the hardware available today* are not going to provide fire managers with the tools to enable them to conduct fire suppression planning based on the resultant predicted fire behaviour. The level of detail of data (type and resolution of parameters and variables) required for input into these models will not be generally available for some time and will necessarily have a high degree of imprecision.

The basis for fire behaviour models of operational use is unlikely to be one of purely physical origin, simply because of the computational requirements to solve the equations of motion at the resolutions necessary to ensure model stability. Approximations do and will abound in order to improve computational feasibility and it is these approximations that lessen the confidence users will have in the final results. Such approximations span the gamut of the chemical and physical processes involved in the spread of fire across the landscape; from the physical structure of the fuel itself, the combustion chemistry of the fuel, the fractions of species within a given volume, turbulence over the range of scales being considered, to the chemical and thermal feedbacks within the atmosphere.

It is most likely that for the foreseeable future operational models will continue to be of empirical origin. However, there may be a trend towards hybrid models of a more physical nature as the physical and quasi-physical models are further developed and refined.

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Table 1: Outline of the major biological, physical and chemical components and processes occurring in a wildland fire and the temporal and spatial (vertical and horizontal) scales over which they operate.

Type	Time scale (s)	Vertical scale (m)	Horizontal scale (m)
Combustion reactions	0.0001 - 0.01	0.0001 - 0.01	0.0001 - 0.01
Fuel particles	-	0.001 - 0.01	0.001 - 0.01
Fuel complex	-	1 - 20	1 - 100
Flames	0.1 - 30	0.1 - 10	0.1 - 2
Radiation	0.1 - 30	0.1 - 10	0.1-50
Conduction	0.01 - 10	0.01 - 0.1	0.01 - 0.1
Convection	1 - 100	0.1 - 100	0.1 - 10
Turbulence	0.1 - 1000	1 - 1000	1 - 1000
Spotting	1 - 100	1 - 3000	1 - 10000
Plume	1 - 10000	1 - 10000	1 - 100

Table 2: Approximate analysis of some biomass species (Shafizadeh, 1982).

Species	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Other (%)
Softwood	41.0	24.0	27.8	7.2
Hardwood	39.0	35.0	19.5	6.5
Wheat straw	39.9	28.2	16.7	15.2
Rice straw	30.2	24.5	11.9	33.4
Bagasse	38.1	38.5	20.2	3.2

Table 3: Summary of physical models (1990-present) discussed here.

Model	Author	Year	Country	Dimensions	Plane
Weber	Weber	1991	Australia	2	XY
AIOLOS-F	Croba <i>et al.</i>	1994	Greece	3	-
FIRETEC	Linn	1997	USA	3	-
Forbes	Forbes	1997	Australia	1	X
Grishin	Grishin <i>et al.</i>	1997	Russia	2	XZ
IUSTI	Larini <i>et al.</i>	1998	France	2	XZ
PIF97	Dupuy <i>et al.</i>	1999	France	2	XZ
LEMTA	Sero-Guillaume <i>et al.</i>	2002	France	2(3)	XY
UoS	Asensio <i>et al.</i>	2002	Spain	2	XY
WFDS	Mell <i>et al.</i>	2006	USA	3	-

Table 4: Summary of quasi-physical models (1990-present) discussed here.

Model	Author	Year	Country	Dimensions	Plane
ADFA I	de Mestre	1989	Australia	1	X
TRW	Carrier	1991	USA	2	XY
Albini	Albini	1996	USA	2	XZ
UC	Santoni	1998	France	2	XY
ADFA II	Catchpole	1998	Aust/USA	2	XZ
Coimbra	Vaz	2004	Portugal	2	XY

Table 5: Summary of all models

Model	No.	Domain Size	Resolution (m)				CPU	Simulation	Computation	Comment
	Dimensions	(x × y × z)	Δx	Δy	Δz	Δt	No. & Type	Time(s)	Time (s)	
<i>Physical</i>										
Weber	2	?	?	-	-	?	?	?	?	
AIOLOS-F	3	10 × 10 × ? km	?	?	?	?	?	?	?	< real time
FIRETEC	3	320 × 160 × 615 m	2 m	2 m	1.5 m	0.002 s	128 nodes	?	?	>> real time
Forbes	2	?	?	?	-	?	?	?	?	
Grishin	2	50 × - × 12 m	?	-	?	?	?	?		700 K isotherm
IUSTI	2	2.2 × - × 0.9 m	0.02	-	0.09	?	?	?	?	500 K isotherm
PIF97	2	200 × - × 50 m	0.25		0.25	1 s	P4 2GHz	200 s	48 h	500 K isotherm
LEMTA	2	?	?	?	-	?	‘PC’	?	?	≈ real time
UoS	2	?	1.875 m	1.875 m	-	0.25μs	?	?	?	
WFDS	3	1.5 × 1.5 × 0.2 km	1.5 m	1.5 m	1.4 m	-	11 nodes	100 s	25 h	
<i>Quasi-physical</i>										
ADFA I	1	?	?	-	-	?	?	?		
TRW	2	?	?	?	-	?	?	?	?	
Albini	2	?	?	-	?	?	?	?	?	
UC	1	1 × 1 × - m	0.01 m	0.01	0.01	0.01 s	Sun Ultra II	144 s	114 s	500 K isotherm
ADFA II	2	?	?	-	?	?	?	?	?	
Coimbra	2	?	?	?	?	?	?	?	?	

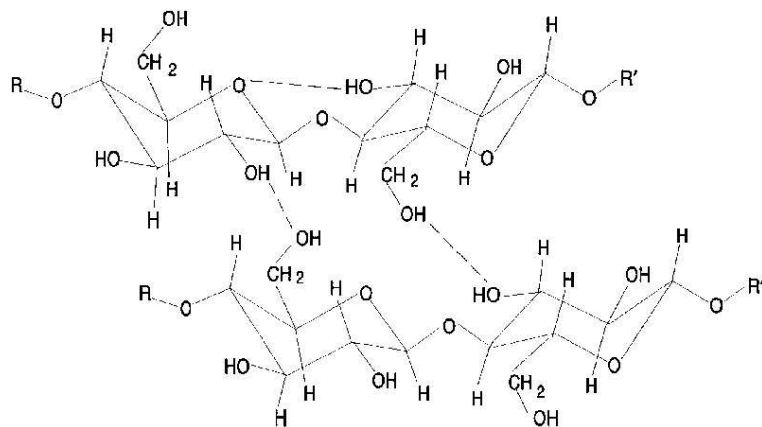


Figure 1: Schematic of chemical structure of portion of neighbouring cellulose chains, indicating some of the hydrogen bonds (dashed lines) that may stabilise the crystalline form of cellulose (Source: Ball et al. (1999))

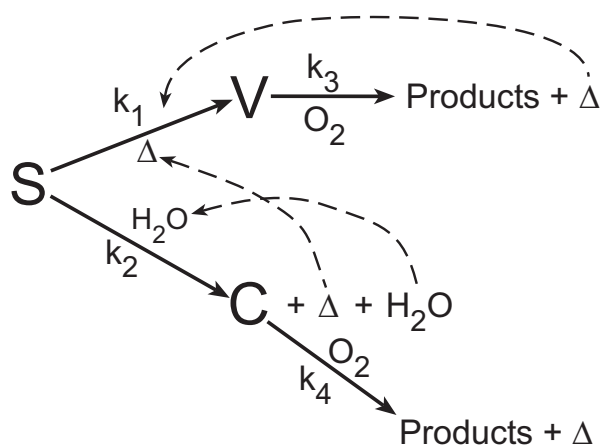


Figure 2: Schematic of the competing paths possible in the thermal degradation of cellulose substrate (S). Volatilisation into levoglucosan (V) in the absence of moisture is endothermic. Subsequent oxidation of levoglucosan into products is exothermic. Char formation (C) occurs at a lower activation energy in the presence of moisture. This path is exothermic and forms water. Chemical and thermal feedback paths (dashed lines) can encourage either volatilisation or charring. (After di Blasi (1998); Ball et al. (1999))